

Citation for published version:

Hussain, A, Calabria-Holley, J, Lawrence, R & Jiang, Y 2019, 'Hygrothermal and mechanical characterisation of novel hemp shiv based thermal insulation composites', *Construction and Building Materials*, vol. 212, pp. 561-568. <https://doi.org/10.1016/j.conbuildmat.2019.04.029>

DOI:

[10.1016/j.conbuildmat.2019.04.029](https://doi.org/10.1016/j.conbuildmat.2019.04.029)

Publication date:

2019

Document Version

Peer reviewed version

[Link to publication](#)

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Hygrothermal and mechanical characterisation of novel hemp shiv based thermal insulation composites

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Abstract

This study focuses on the development of advanced water resistant bio-based composites with enhanced hygrothermal performance for building applications. The highly porous structure of hemp shiv is responsible for low thermal conductivity and allows the material to adapt to varying humidity conditions providing comfortable indoor environment. However, the pore network and the hydrophilic nature of hemp shiv affects the compatibility and durability of the material in presence of excess moisture conditions. In this work, novel hemp shiv composites were prepared in a starch based or silica based matrix and characterised for their hygroscopic, thermal and mechanical properties. The hemp shiv based composites were resistant to water yet permeable to vapour and showed excellent moisture buffering capacity when compared to conventional hemp-lime composites. The composites prepared were light weight with low thermal conductivity values of 0.051-0.058 W/mK and showed good mechanical performance. Hemp shiv composites with superior hygrothermal characteristics have immense potential as robust thermal insulation building materials.

Keywords: Hemp shiv; hygrothermal; moisture buffering; vapour permeability; thermal conductivity; bio-based composites.

1. Introduction

Bio-based materials have gained interest in the building industry since the last decade due to their hygroscopic and insulation properties. The use of these materials not only enhances the energy efficiency of the building but is also beneficial for the health and comfort of the occupants [1,2]. Using bio-based materials can also have a positive impact on the environment since they have the ability to

capture CO₂ from the atmosphere during their lifetime. When these materials are used to produce building materials, the sequestered CO₂ is locked up within the building resulting in the production of extremely low embodied energy materials [3].

Several studies have discussed the moisture buffering property of bio-based materials. The ability to absorb and release moisture in response to changes in surrounding relative humidity can impact indoor comfort levels and reduce the energy demands for air conditioning [4]. Creating a vapour permeable wall and maintaining indoor relative humidity levels between 40 and 60% can have a positive impact on wellbeing of residents, reducing bacterial growth, allergies and controlling respiratory problems [5].

Numerous studies have reported the use of hemp shiv in the production of hemp based composites with majority of the research being conducted on hemp lime [6–12]. The hydrophilicity of hemp shiv leads to competition with hydraulic lime that needs water for hydration and cohesion [13,14]. As a result, the hemp lime blocks need long drying times of approximately several months to a year which are not preferred on an industrial scale [13]. Hemp lime walls tend to have a powdery inner core resulting in poor interfacial adhesion as hydraulic binders like lime or cement undergo incomplete hydration. The thermal conductivity of hemp based composites can be influenced by binder type, aggregate to binder ratio and water content [14,15].

The large water absorption capacity of hemp shiv is due to its highly porous structure and its chemical composition. Hemp shiv has low bulk density (90-110 kg/m³) and high porosity (76-78%) due to the structure of the plant stem from which they are derived [16]. Moreover, the presence of high amounts of cellulose (44%) and hemicellulose (27%) in hemp shiv contributes to the presence of hydrophilic hydroxyl groups in their chemical composition [17]. High moisture sensitivity in bio-based materials can be responsible for colonial fungal growth leading to degradation of their cell wall and the durability of the material can be compromised [18]. Furthermore, high water absorption capacity of these materials can affect the manufacturing quality of the end product if they encounter humid surroundings or come in contact with water.

On the positive side, the highly porous structure of hemp shiv is responsible for the excellent hygroscopic and insulation properties of the material. Therefore, there is a need to develop new hemp based composites to address the existing issues as well as to retain the maximum insulating and moisture buffering properties of the bio-based aggregate. The use of silica based coatings on hemp shiv has proven to be successful in enhancing its hydrophobicity [19,20]. Application of silica based coatings have successfully shown to lower the water absorption capacity of hemp shiv yet retaining its moisture buffering ability due to presence of small pores that are not blocked by the coating [21,22]. We have reported recently the dual functional use of silica both as a binding matrix and as a hydrophobic treatment on hemp shiv for the development of new bio-based building composites [23]. The work done here has been carried out under the ISOBIO project which aims to develop bio-based insulation panels with low embodied energy for both new buildings and retrofitting to existing buildings.

This research focuses on the development of water resistant hemp shiv based composites for use as a building thermal insulator. The novel composites were produced either in starch matrix or silica matrix without using any additional mineral binders. The composites have been characterised for their hygroscopic, thermal insulation, water resistance and mechanical properties.

2. Materials

2.1 Bio-aggregate

Hemp shiv was received from CAVAC, an agricultural cooperative based in north-west France. The aggregates had mean width (W50) 2.3 mm and mean length (L50) 7.6 mm. The maximal width was 4.0 mm and maximal length was 13.1 mm. The bulk density at dry state was 85-90 kg/m³. The aggregates were used as received without undergoing any surface modification or drying. The hemp shiv aggregates used for this study are shown in Figure 1.



Figure 1. Hemp shiv aggregates used in this study.

2.2 Treatment formulation

Tetraethyl orthosilicate (TEOS, 98%), nitric acid (70%), hexadecyltrimethoxysilane (HDTMS, 85%) and absolute ethanol were received from Sigma-Aldrich. For the preparation of the hydrophobic treatment, the sol-gel process was followed. 1M of TEOS was added as the silica component to a mixture of 4M distilled water, 4M of absolute ethanol and 0.005M of nitric acid. 0.015M of HDTMS was added to the above mixture as the hydrophobic agent. The sol was vigorously stirred at 40 °C and atmospheric pressure for nearly 2 hours. The sols were allowed to age for 96 hours in closed container at room temperature before the treatment process. Figure 2 shows the surface of hemp shiv before and after the silica treatment.

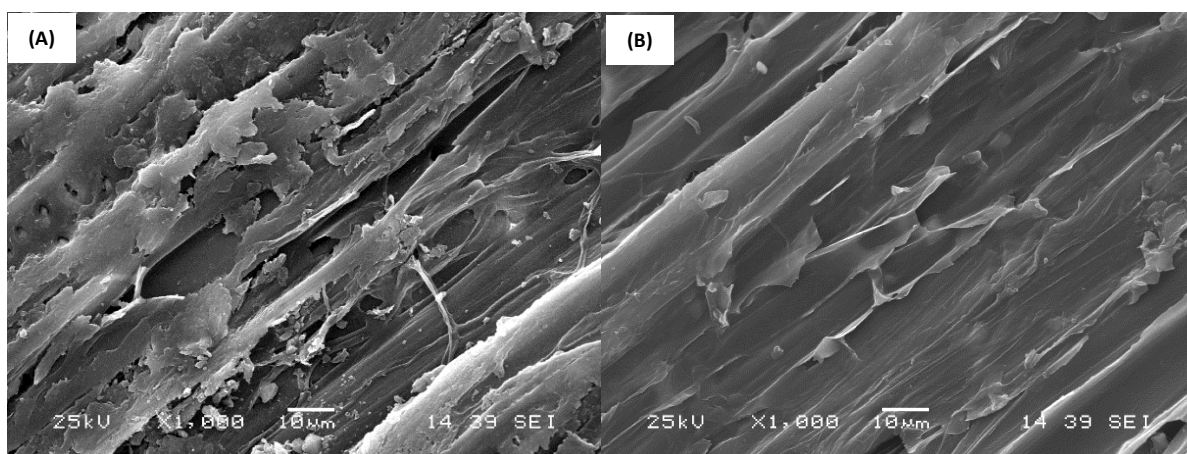


Figure 2. Micrographs of hemp shiv surface (A) untreated, (B) after hydrophobic silica treatment.

2.3 Composite formulations

Composite C1 - Hemp shiv aggregates and silica treatment as binder: Mixing of the constituent materials, raw hemp shiv and sol was carried out manually to achieve a uniform mixture. The weight ratio for raw hemp shiv: binder was 5:1. The mass of the materials was pre-calculated to target a final density of 175 kg/m³ for the composites. Aggregates of hemp shiv were mixed with the sol and then placed into a phenolic ply mold of desired dimension, tamped down and left for overnight in the oven at 80 °C. The specimens were removed from the molds and transferred to a conditioning room at 19 °C and 50% relative humidity.

Composite C2 - Treated hemp shiv aggregates and bio-based binder: Prior to composite preparation, hemp shiv aggregates were dipped in the sol for 10 min and then removed and transferred onto an open tray. The treated aggregates were dried at 80 °C overnight. C2 composites were then prepared by mixing treated hemp shiv aggregates with a bio-based binder formulated by CAVAC using a starch derivative and a crosslinker. The weight ratio for treated hemp shiv: binder was 9:1. The mixture was placed into a steel mold of desired dimension with a target density of 240 kg/m³, compacted at 0.5 MPa using a hot press (PressMasters 40T GEM series). The upper and lower plates were then heated to 180 °C and the temperature was maintained for one hour. The specimens were demolded after cooling down to room temperature and then transferred to a conditioning room at 19 °C and 50% relative humidity.

Composite C3 – raw hemp shiv aggregates and bio-based binder: C3 composites were prepared by mixing raw hemp shiv aggregates with the same bio-based binder as in formulation C2. The weight ratio for raw hemp shiv: binder was 9:1. The mixture was placed into a steel mold of desired dimension with a target density of 200 kg/m³, and the rest of the conditions for the manufacturing process using the thermal press remained constant as for Composite C2. The specimens were demolded after cooling down to room temperature and then transferred to a conditioning room at 19 °C and 50% relative humidity. The target density of C3 is lower than C2 due to the absence of silica treatment that increases the mass of hemp shiv aggregates by 18 ± 1%. C3 is referred to as the untreated (baseline) composite later in the text.

The prepared composites C1, C2 and C3 have different final densities due to the type of binder used which determines their production process. C1 uses a rather simple process involving mixing hemp shiv and silica-based binder whereas C2 and C3 use a polysaccharide binder that needs to be cured using a thermal press. The aggregate and the binder content are different in the two production processes which in turn affect their final density. Although C2 and C3 have similar binder content and binder to aggregate ratio, the density of C2 is higher due to the hydrophobic treatment of hemp shiv aggregates. The composites were prepared with the aim of achieving lightweight and stable coherent blocks with minimum density. Targeting a low composite density would be beneficial to achieve maximum thermal insulation and moisture buffering capacity of hemp shiv.

2.4 Methods

2.4.1 Vapour permeability

The ability of a porous material to transfer moisture due to a vapour pressure gradient can be expressed by the vapour permeability of the material. The transfer of moisture during this process can take place due to three factors: diffusion (self-collision of water molecules), effusion (collision of water molecules with the pore walls) and liquid transfer (associated with capillary condensation) [24].

The water vapour permeability and the diffusion resistance factor of thermal insulation materials can be measured using the British Standard (BS EN 12086) [25] under isothermal conditions (23 °C) and at two sets of relative humidity: dry cup and wet cup. Three samples with dimensions 100mm x 100mm and thickness 20mm were conditioned for at least 6 h at 23 °C and 50% relative humidity to reach constant mass. The samples were then placed on plastic containers filled either with desiccant (dry cup test) or salt solution (for wet cup test). The sides of the samples were properly sealed to achieve unidirectional moisture flow. The test assembly is shown in Figure 3.

The test assembly containing the sealed specimens were placed in a climate chamber where the temperature and humidity were controlled constantly. For the dry cup test, the relative humidity inside the container was maintained between 0-2% using silica beads and the climate chamber was set at 50% relative humidity. For wet cup test, the relative humidity inside the container was maintained at 93% using saturated KNO₃ salt solution and the climate chamber was set at 50%.



Figure 3 Test assembly of hemp composites for vapour permeability testing.

The test assembly was then conditioned in the climate chamber for 24 h. The partial pressure gradient between the container and the climate chamber drives the vapour through the specimen. The test assembly was weighed every 24 h until three successive determinations of change in mass per unit time for each specimen was within $\pm 5\%$ of its mean value.

The rate of change in mass (G) (mg/hr) was calculated using the equation:

$$G_{1,0} = \frac{(m_1 - m_0)}{(t_1 - t_0)} \quad \text{Eq (1)}$$

where m_1 (mg) is the mass of the test assembly at time t_1 , m_0 is the mass of the test assembly at time t_0 . G is the mean of at least three successive determinations of $G_{1,0}$ (mg/h) provided $G_{1,0}$ is within $\pm 5\%$ of G .

The water vapour transmission rate (g), water vapour permeance (W), water vapour resistance (Z), water vapour permeability δ and water vapour diffusion resistance factor (μ) was calculated using the equations in the British Standard (BS EN 12086) [25].

2.4.2 Moisture buffering

The moisture buffering ability of a hygroscopic material can be measured by the moisture buffer value (MBV). Hygroscopic materials have the ability to adsorb and release moisture responding to changes in surrounding relative humidity in order to create an equilibrium. Moisture buffering capacity can regulate the fluctuations in humidity in internal spaces.

The MBV was measured according to the NORDTEST method [26]. This method was used to measure the practical moisture buffer value of the specimens under dynamic conditions. This value

represents the amount of moisture adsorption and desorption, per unit open surface area, under daily cyclic variation of relative humidity according to following equation:

$$MBV = \frac{\Delta m}{A \cdot (RH_{high} - RH_{low})} \quad \text{Eq (2)}$$

where MBV: moisture buffer value ($\text{g}/(\text{m}^2 \text{ \%RH})$), Δm is moisture uptake/release during the period (kg), A is open surface area (m^2), $RH_{high/low}$ is relative humidity level (%) respectively.

The specimens were tested in triplicates. Each sample was exposed only from a single side having a surface area of at least 100 mm x 100 mm. The other five sides of the sample were sealed with aluminium foil tape. The thickness of each sample was the actual product thickness ranging between 50-60 mm.

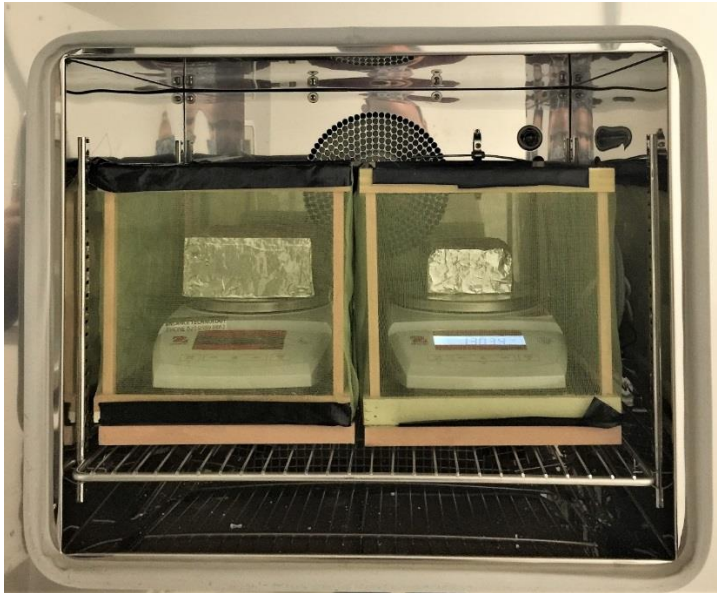


Figure 4. Moisture buffering setup in climate chamber.

A climate chamber (ACS Angelantoni Test Technologies, model DY110 SP, Italy) was used for the MBV experiment that can be controlled in the range -40 to 180 °C and 10 to 95% relative humidity. The samples were preconditioned at 23 °C and 50% relative humidity for at least 6 hours before the test. The samples were then exposed to cyclic relative humidity conditions where each 24h cycle was a combination of 8h exposure to 75% relative humidity and 16h exposure to 33% relative humidity at 23 °C temperature. Temperature and relative humidity were measured and maintained constantly with the sensor of the climate chamber. The measurement of mass was performed by a precision scale with readability and repeatability of 0.001grams (g). The sample mass was logged every min by a

computer connected to the scale. A screen was placed around the balance to minimise the influence of air movement over the sample surface during the test as seen in Figure 4. The wind speed was measured by an anemometer and found to be 0.1 m/s at the sample surface. The experiment was continued until the change in mass between three consecutive cycles was not greater than 5%. The surface vapour resistance was assumed to be constant during the test.

2.4.3 Thermal conductivity

The thermal conductivity of the samples was measured using a hand-held measuring instrument ISOMET 2114 which is used for direct measurement of heat transfer properties of a wide range of isotropic materials including cellular insulating materials, plastics, glasses and minerals. The ISOMET is equipped with two types of measurement probes: needle probes for soft materials, and surface probes for hard materials. It applies a dynamic measurement method, which enables a reduced measurement time in comparison with steady state measurement methods. Measurement is based on analysis of the temperature response of the analysed material to heat flow impulses. Heat flow is induced by the electrical heating of a resistor heater inserted into the probe which is in direct heat contact with the tested specimen. In order to obtain the best measurement accuracy on specific materials, surface probes are used for measurement on solid and hard materials.



Figure 5. Thermal conductivity setup using ISOMET.

For measuring the thermal conductivity of the composite samples, the surface probe was used which is a heating plate as seen in Figure 5. The evaluation of thermal conductivity and heat capacity is based on periodically sampled temperature records as a function of time. The samples had a flat surface with dimensions of at least 100 x 100 mm. Greater accuracy of surface flatness is required

with increasing thermal conductivity of the tested material. The minimal thickness of the samples was 50 mm.

2.4.4 Water absorption

The short term water absorption of the specimens was determined by the British Standard EN 1609:2013 [27]. The specimens were preconditioned for at least 6 h at 23 °C and 50% relative humidity. The specimens were partially immersed in water for a period of 24 hours by applying a sufficient load on the top face as seen in Figure 6A. The water level was maintained such that the bottom face of the specimen was 10 ± 2 mm below the surface of water during the entire test. After 24 ± 30 min, the test specimen was removed and drained for 10 min by placing it vertically on a mesh, inclined at an angle of 45° as shown in Figure 6B. This step allowed draining any excess water adhering to the surface but not absorbed by the specimen. The test was carried out at 23 ± 2 °C and 50 ± 5 % relative humidity. The specimens were tested in triplicates. The test specimens had a bottom surface area of at least 100 mm x 100 mm and the thickness of each sample was the actual product thickness ranging between 50-60 mm.

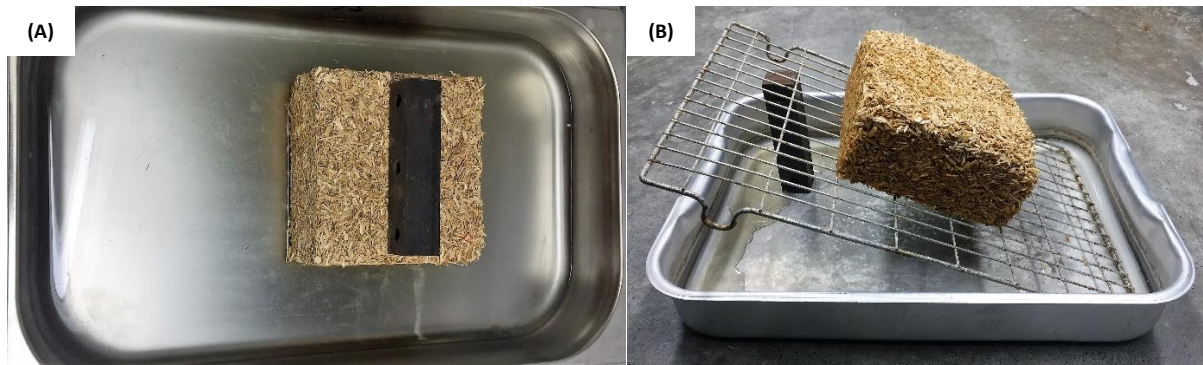


Figure 6. Water absorption test showing (A) sample placed in water for 24 hours, (B) draining at an inclined angle.

The water absorption was calculated as the change in mass according to the following equation:

$$WA = \frac{m_{24} - m_0}{A_p} \quad \text{Eq (3)}$$

where WA is the water absorption (kg/m^2), m_0 is the initial mass of the test specimen (kg), m_{24} is the mass of the test specimen after partial immersion for 24 h (kg), A_p is the bottom surface area of the test specimen (m^2).

The percentage of water absorption was calculated according to the following equation:

$$WA \% = \frac{m_{24} - m_0}{m_0} * 100 \quad \text{Eq (4)}$$

where $WA\%$ is the water absorption percentage.

2.4.5 Compression

Compressive tests were conducted on 100 mm cube samples using an Instron 50 KN testing rig at a controlled displacement of 3 mm/min; the inbuilt instrumentation was used to both record load and platen displacement at a resolution of one data point per 0.1 s. Prior to compression testing, the samples were placed in a conditioning room at 19 °C and 50% relative humidity for at least 24 hours. The tests were performed in triplicates and the average reading was reported.

3. Results and discussion

The transfer of moisture takes place in porous materials when a vapour pressure gradient is present between the opposite surfaces (top and bottom) of the material. The water vapour permeability results of the hemp shiv based composites are summarised in Table 1 for both dry cup and wet cup tests. The kinetics of mass change during the water vapour permeability test is presented in Figure 7 for the composites. From the vapour diffusion resistance μ results, it was found that for the dry cup, C2 had the lowest value of μ , and for the wet cup C1 had the lowest value of μ . All the composites showed higher permeability (lower resistance factor) during higher relative humidity conditions with the maximum increase observed in C1 composite.

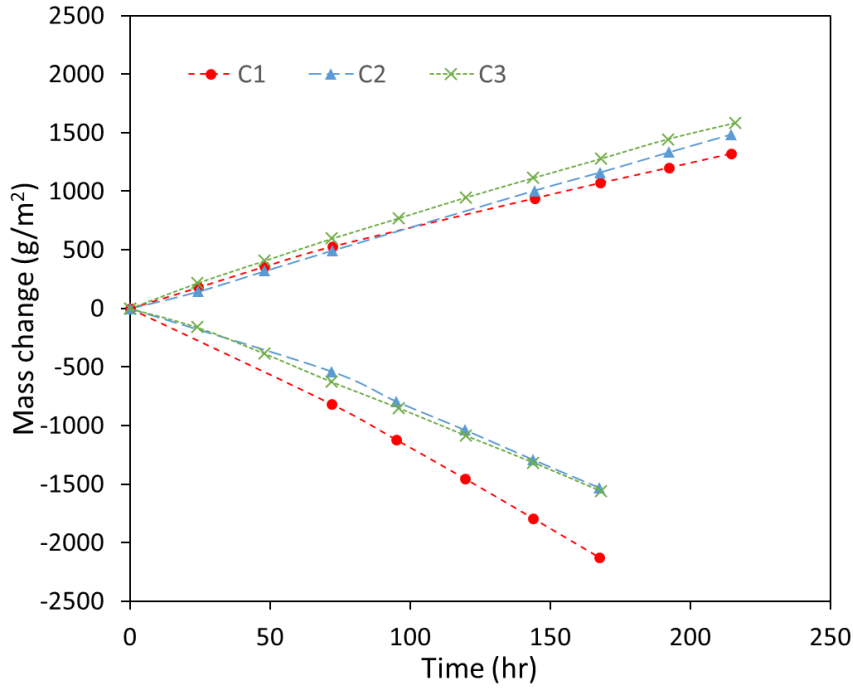


Figure 7. Mass change of the specimens during the vapour permeability test.

Table 1. Vapour permeability results of the hemp shiv based composites.

Parameters	C1 composite		C2 composite		C3 composite	
	Dry cup	Wet Cup	Dry cup	Wet Cup	Dry cup	Wet Cup
Water vapour transmission rate, g (mg/hr)	5675.65	15538.89	7224.33	9605.63	6343.75	9833.33
Water vapour permeance, W (mg/m².hr.Pa)	4.22	12.84	5.37	7.94	4.72	8.13
Water vapour resistance, Z (m².hr.Pa/mg)	0.24	0.08	0.18	0.13	0.21	0.12
Water vapour permeability δ (mg/m.hr.Pa)	0.08	0.26	0.11	0.16	0.09	0.16
Water vapour resistance factor μ	8.42	2.77	6.62	4.48	7.54	4.37

It can be seen the hydrophobic treatment in composites C1 and C2 does not significantly affect the water vapour permeability results when compared to the untreated C3 composites. The increase in

the water vapour permeability at higher humidity level is related to the enhanced transport of moisture. This phenomenon is induced by the transfer of liquid in the microscopic pores of the material that are filled with water due to capillary condensation [24]. For materials that show hysteresis in their sorption isotherm, it has been reported earlier that their water vapour permeability is dependent on the moisture content [28].

The fluctuations in humidity within internal spaces of a building can be regulated by the moisture buffering ability of the construction materials. The kinetics of mass change for the MBV test is presented in Figure 8. The mass change was calculated per m^2 exposed surface of the samples and plotted against time. The sampling frequency was every 1 min and the data is plotted using a running average of every 60 min.

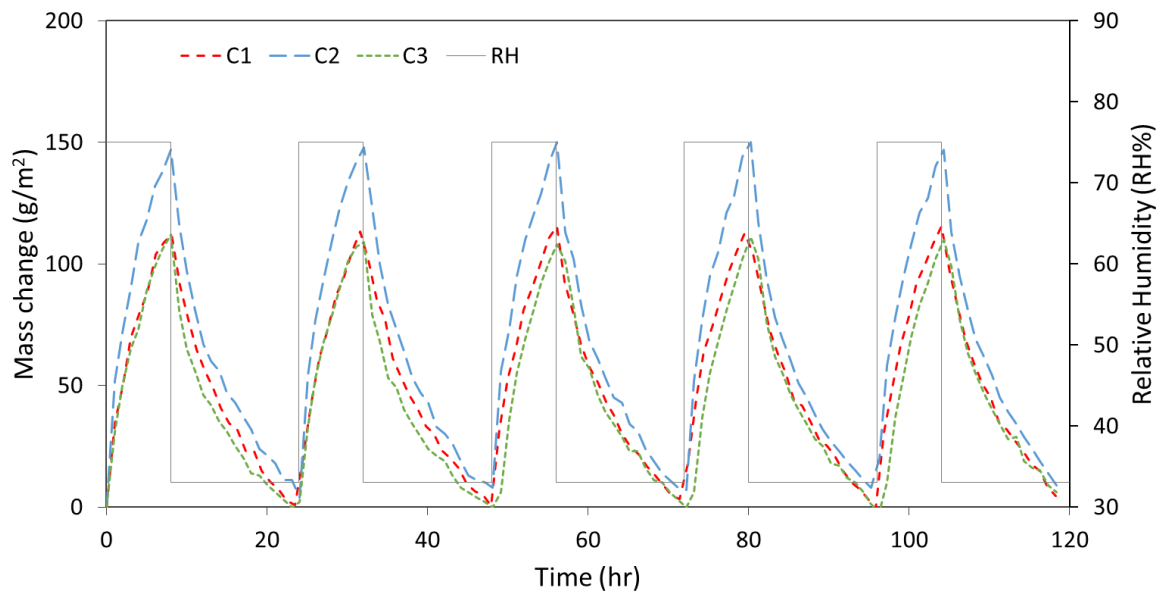


Figure 8. Mass change of the composites when exposed to varying relative humidity at 23 °C.

Table 2. MBV values of the composites using NORDTEST.

Sample	MBV (g/m ² .RH) ³⁰⁸
C1	3.07 ± 0.05
C2	3.63 ± 0.01
C3	2.93 ± 0.02

The moisture buffering capacity of the materials can be classified in terms of their moisture buffer value (MBV) as: Excellent (MBV ≥2.0 g/m²RH), Good (MBV 1.0-2.0 g/m²RH), Moderate (MBV 0.5-1.0 g/m²RH), Limited (MBV 0.2-0.5 g/m²RH) and Negligible (MBV ≤0.2 g/m²RH) [29]. From Table 2, it can be seen that all the prepared composites showed “excellent” moisture buffering capacity with the highest MBV obtained for the C2 composites. The MBV of all hemp shiv composites (C1, C2 and C3) is higher than previously reported MBV for hemp concrete (1.75-2.15 g/m²RH) [10,11,30]. This can be attributed to the higher hemp shiv: binder ratio in the prepared composites inducing lower density and enhanced permeability.

The thermal properties were analysed using a dynamic measurement system and they are reported in Table 3. It was observed that the thermal conductivity was in the range 0.051-0.058 W/mK and the thermal diffusivity ranged 0.28-0.35 m²/s. The thermal conductivity values were lower when compared to the values for hemp lime composites (0.08 – 0.16 W/mK) previously reported in literature [31,32]. An obvious reason for the low conductivity is that the density of the prepared composites is much lower than hemp-lime composites. The higher hemp shiv: binder ratio used for the prepared composites takes greater advantage of the insulation properties of hemp shiv. The increased hemp shiv content in the matrix results in higher porosity thereby producing low density composites when compared to hemp-lime.

The specific heat capacity for the composites ranged from 760 – 1050 J/kg.K (Table 3). It can be seen that C1 and C3 composites have a high specific heat capacity for their respective densities. A hemp concrete composite is reported to have specific heat capacity of 1000 J/kg.K for a density of 413 kg/m³ [10]. C1 composite in comparison to hemp concrete has less than half its density but a higher

heat capacity. This could be attributed to the presence of chemically bound water (heat capacity 2200 J/kg.K) [33] in the silica coating that may affect the specific heat of the C1 and C2 composites when compared to the untreated C3 composite. In addition to the lowest density of C1 composite, it comprises of a silica matrix as opposed to C2 consisting of a starch matrix, thereby having superior insulating properties.

Table 3. Thermal conductivity data obtained from transient method using ISOMET.

Sample	Thermal conductivity (W/mK)	Thermal diffusivity (10^{-6}) (m^2/s)	Specific heat capacity (J/kg.K)	Bulk Density (kg/m^3)
C1	0.052	0.28	1050.28	175.0 ± 3
C2	0.057	0.30	782.71	240.0 ± 5
C3	0.053	0.35	763.00	200.0 ± 5

The relationship between density and thermal conductivity of the three prepared hemp shiv composites is shown in Figure 9. It is clearly seen that increasing the density increases the thermal conductivity of the composite which has also been previously reported in several studies [31,32,34].

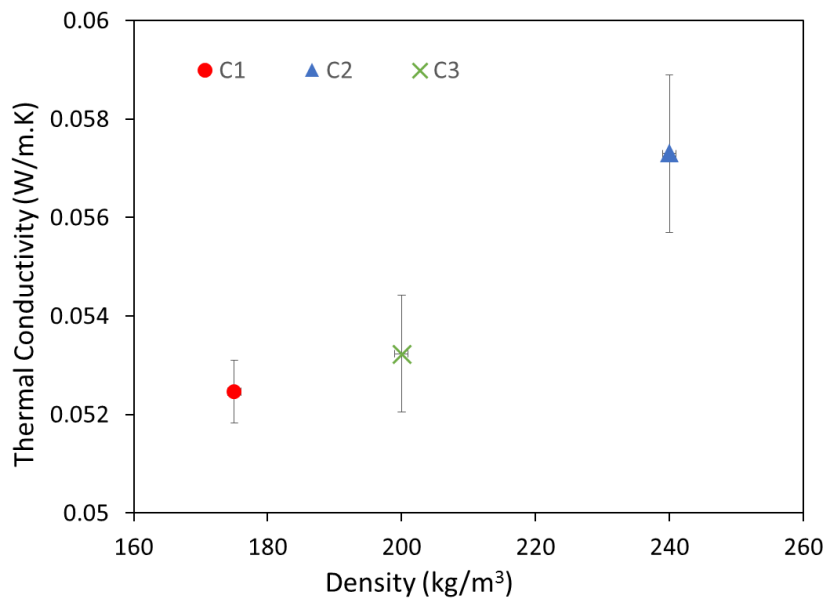


Figure 9. Thermal conductivity vs density of the composites.

The water absorption of the composites is calculated in two ways: (i) as change in mass over exposed surface area (WA) using Equation 3 and; (ii) as percentage of absorption with respect to initial mass

(WA%) using Equation 4. The water absorption results are presented in Table 4. C3 shows the highest values for WA and WA% due to the absence of hydrophobic silica treatment on hemp shiv in the composites. For C2, the hydrophobic treatment reduced the WA by 50% and the WA% reduced by 123%. For C1, the reduction in water absorption is not as significant as C2. This is due to the fact that C1 has a much lower density than C2, therefore having more voids in the composite where water may get trapped during the test. Nevertheless, the C1 water absorption values show that the treatment was still effective and absorbed less water when compared to untreated C3 composite.

Table 4. Water absorption measurements of composites.

Sample	WA (kg/m ²)	WA%
C1	18.48 ± 0.1	180.41 ± 2.2
C2	11.04 ± 0.6	98.02 ± 3.5
C3	22.11 ± 0.7	221.10 ± 1.3

The variation reported in hygroscopic properties is clearly a combined effect of multiple factors such as binder type, pre-treatment and density. For instance, the MBV, vapour permeability and water absorption of the composites do not follow a trend with density. C1 having the lowest density has higher MBV and shows lower water absorption when compared to untreated C3. This is mainly the effect of the hydrophobic treatment. On the other hand, C1 and C2 have varying properties due to the difference in their binder type and density.

The stress versus strain curves for the prepared hemp shiv composites are presented in Figure 10. The results show that C3 has a compressive stress of 0.92 ± 0.01 MPa at 30% strain. C2 composites show the highest compressive stress of 1.05 ± 0.04 MPa at 30% strain which is 14% higher than C3. On the other hand, the compressive stress of C1 is 0.49 ± 0.02 MPa at 30% strain which is 47% lower than C2. For all composites, it was observed that higher strain levels lead to further densification of the composites. The behaviour of the composites at varying strain levels (0%, 10%, 50%, after test) are imaged in Figure 11. After the compression test, C1 and C2 composites showed some elastic

behaviour as seen in Figures 11D and 11H. The compressive strength of the prepared composites seemed to vary in line with density.

In general, the prepared light weight composites showed good mechanical performance. The composites attained compressive stress ranging between 0.49 – 1.05 MPa at very low densities (175-240 kg/m³) which are relatively good when compared with other hemp shiv based composites such as hemp-lime (0.02 - 0.39 MPa at density 360 kg/m³) [12], hemp-clay (0.39 at density 373 kg/m³) [35] or hemp-starch (0.4 MPa at density 177 kg/m³) [36]. The prepared composites did not reach failure even at 60% strains, which suggests good interfacial adhesion between the hemp shiv and the matrix.

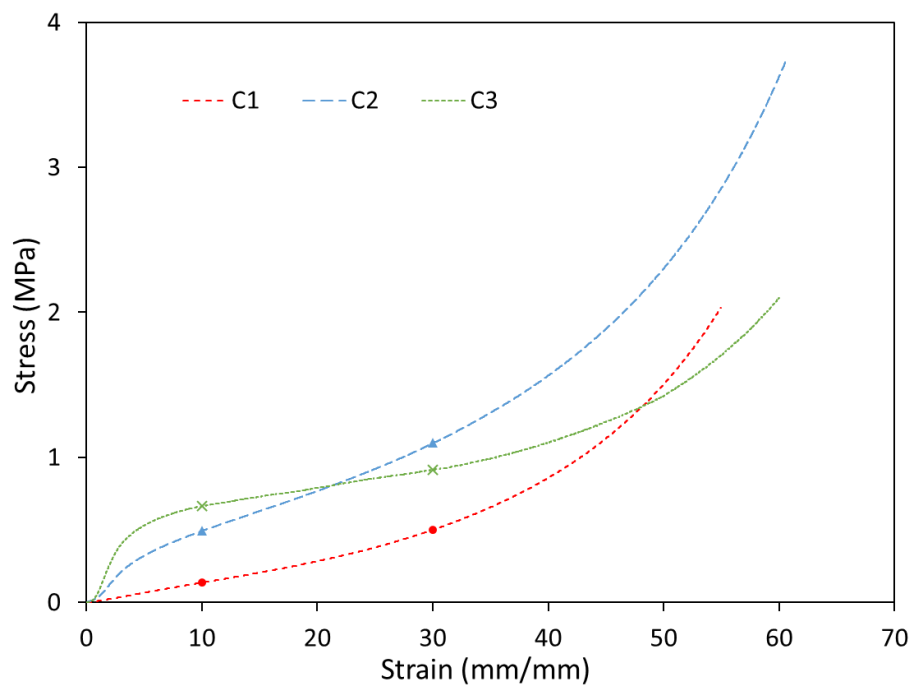


Figure 10. Compressive strength of the hemp based composites.



Figure 11. Compression testing of different hemp shiv composites; C1 at (A) 0% strain, (B) 30% strain, (C) 50% strain, (D) after 50% strain; C2 at (E) 0% strain, (F) 30% strain, (G) 50% strain, (H) after 50% strain; and C3 at (I) 0% strain, (J) 30% strain, (K) 50% strain, (L) after 50% strain.

4. Conclusion

In this work, manufacturing and testing of novel hemp shiv based composites have been reported. The composites showed a significant enhancement of hygrothermal performance when compared to traditional hemp based insulation composites. Vapour permeability and Nordtest results validate that hemp shiv composites retain their hygroscopic and moisture buffering ability even after hydrophobic treatment of the aggregate. The silica treatment reduced the hydrophilicity of hemp shiv as seen with the water absorption tests making them water resistant and less susceptible to degradation. The binding matrix did not degrade the thermal properties, and the prepared composites had thermal

conductivity values of 0.052 W/mK. Preparation of composites with high hemp shiv: binder ratio had a significant benefit for enhancing their thermal insulation properties. The composites showed good mechanical properties as a non-load bearing material and final composites with density as low as 175 kg/m³ were prepared successfully. Using economical methods, high performance hemp shiv based insulation composites have been developed that have great potential in the construction industry by reducing the embodied energy and the in-use energy demands of buildings.

Acknowledgments

The work was supported by the ISOBIO project funded by the Horizon 2020 programme [Grant number 636835 – ISOBIO – H2020-EeB-2014-2015] and the EPSRC Centre for Decarbonisation of the Built Environment (dCarb) [grant number EP/L016869/1]. The authors thank CAVAC for providing the bio-based binder for preparation of the composites. The contents of this publication are the sole responsibility of the authors and can in no way be taken to reflect the views of the European Union. All data are provided in full in the results section of this paper.

Disclosure statement

The authors declare that they have no conflict of interest.

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